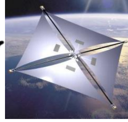

40th IEEE Aerospace Conference 2019

Solar Sails for Planetary Defense & High-Energy Missions

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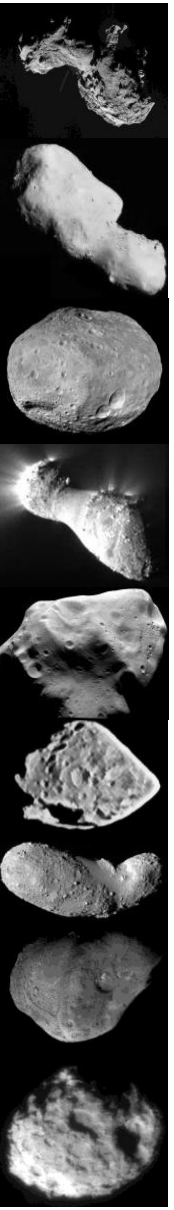


"When you've seen one asteroid,… …or comet…
…you've seen *one* asteroid. …or comet.

until very recently, every asteroid visited looked different from all the others

- there are several approaches to classification but not all connections are understood:
  - spectral information → taxonomy ← ? → composition
  - shape & topography ← ? → interior structure → porosity
  - families ← orbital dynamics ← Yarkovsky → YORP ← ?
- …*however*: each discipline sees a little light at the end of their tunnel
  - *taxonomy*: obvious patterns but composition inferred (cf. 2008 TC_3 / Almaha Sitta)
  - *shapes*: radar – the poor man's flyby – shows >1 "top-like", "cigar", "bi-lobe"…
  - *orbits*: long-term monitoring makes small Yarkovsky & YORP effects quantifiable
- …*corollary*: all these dots & models still need to be connected

➔ **need to study many more asteroids – close-up, soon, affordable**

DLR

getting a handle on asteroids: from target selection* to ground truth

- all current & almost all future small solar system bodies science missions require sample in-situ analysis and/or return

- science can choose to interact with an asteroid – planetary defence *<u>must</u>*

- *<u>all</u>* deflection methods interact with the target asteroid:
  - gravity tractor – ion engine plume impinges on asteroid
  - kinetic impactor – transfers impulse & energy (β-factor)
  - laser ablation – evaporates surface, releases volatiles
  - solar concentrator – evaporates surface, releases volatiles
  - thruster attachment – soft landing of a fuel-laden spacecraft
  - albedo modification – covers or rearranges the surface layers
  - …

→ *characterization by rendezvous with target or closely analog asteroid*

→ *get to know **multiple Near-Earth Asteroids** <u>before</u> “**the one**“!*

*)

images: J.R.C. Garry for ISAS, ESA/DLR, JAXA, NASA/GSFC/LM

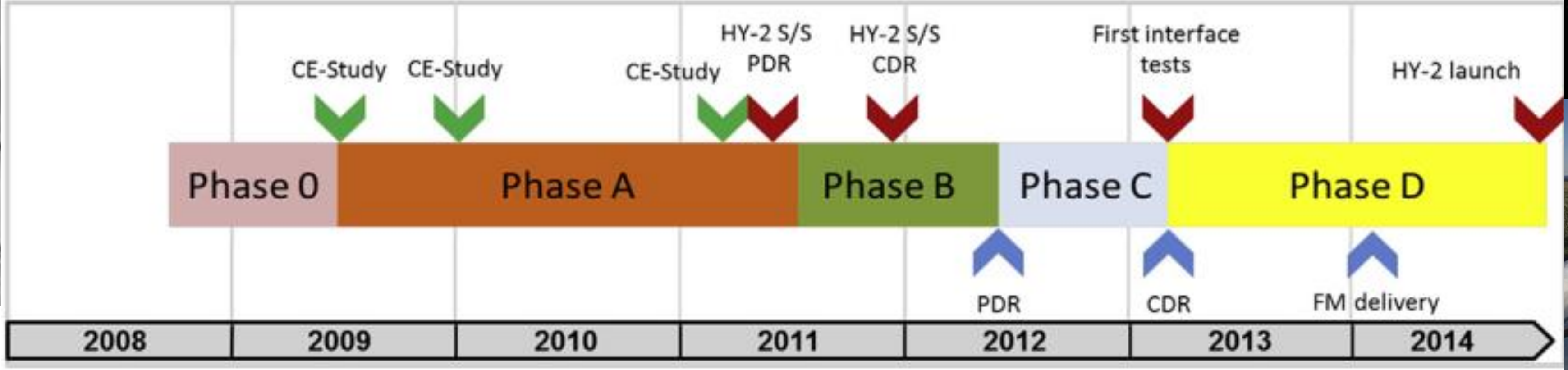
DLR

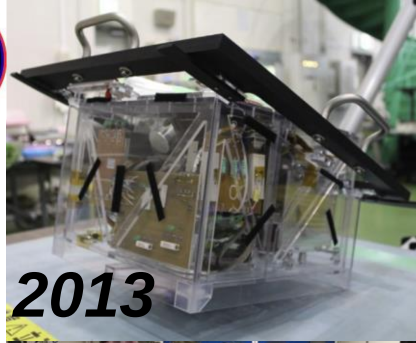
a brief history of…

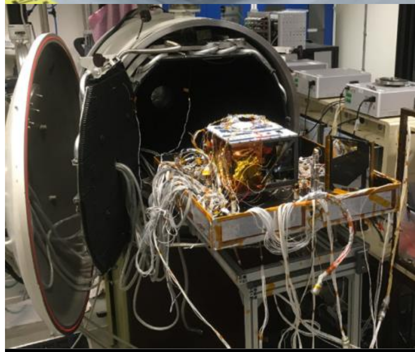
re-discovering responsive space

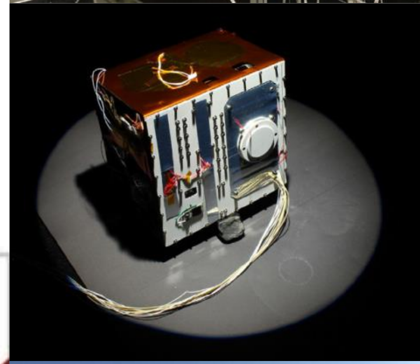
- when (…not if…) an impactor is found, the combination of…
  - extreme inaccessibility of almost all asteroid orbits
  - lead time from a *positive* prediction of impact to the expected impact

  …will put extreme time pressure on the space segment
- very few launch windows & extreme Δv to rendezvous *or* very fast fly-by
- 60 years ago, real spaceflight was *invented* within ≈2 years from the word ‘go‘
- recent science missions take ≈20 years to design & build (e.g. Rosetta, Cassini)
- MASCOT went forward to the past: 2 years from PDR to FM delivery

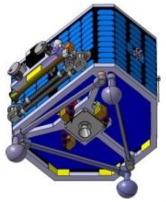




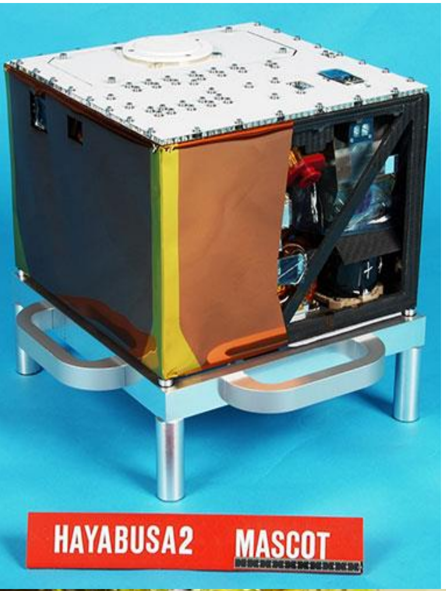


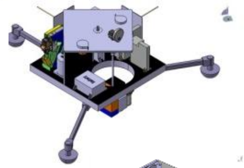


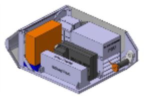
figures: Grimm et al, 2018
USAF via The Space Review

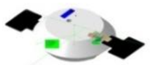


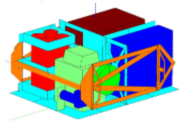
‘now-term’ technology: a Lander as an Instrument – MASCOT

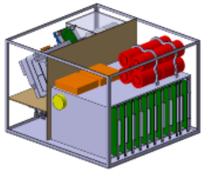




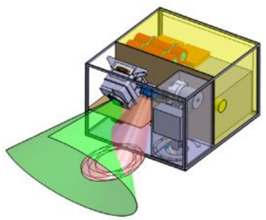


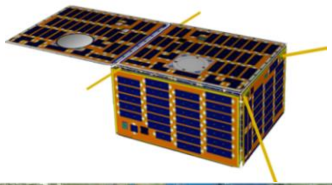






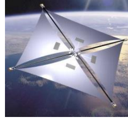
- MASCOT – ***M***obile ***A***steroid ***S***urface S***co***u***t***
  - 2008-2011: concept & CE studies
  - 2012-2014: from paper design to FM delivery
  - 2014-2018: cruise to km-sized PHA (162173) Ryugu aboard JAXA’s HAYABUSA2
- landed on October 3rd, 2018 for its 17 hours scouting mission (*during IAC 2018*)
- with precursor and follow-on studies, e.g. MARCOPOLO or MASCOT2 for AIM (AIDA), a ready-to-go repertoire for many missions has already been created





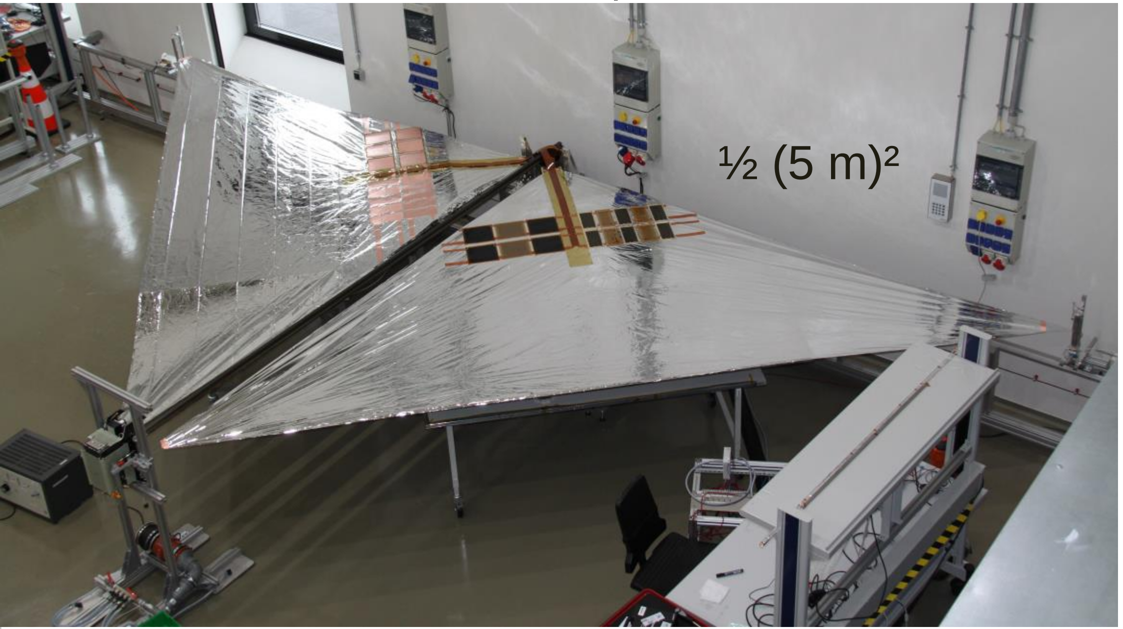
- lander at the instrument level of a mainstream mission
- serves 4 full planetary science quality instruments
- high degree of design re-use
- constraints-driven design
- high-density design
- nanospacecraft

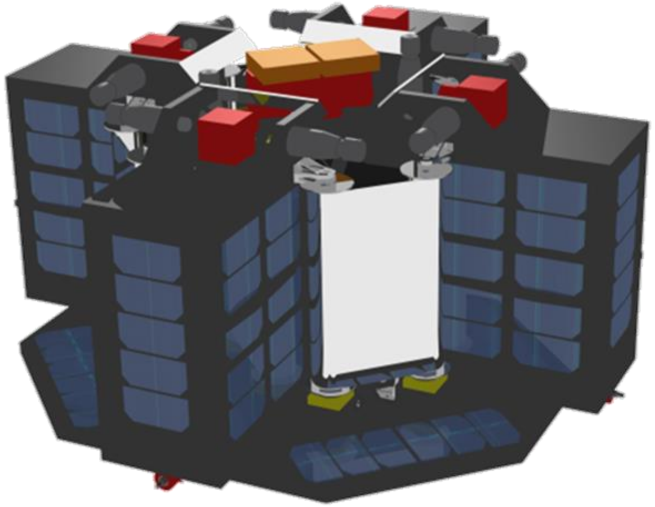
figures: DLR, JAXA, ESA



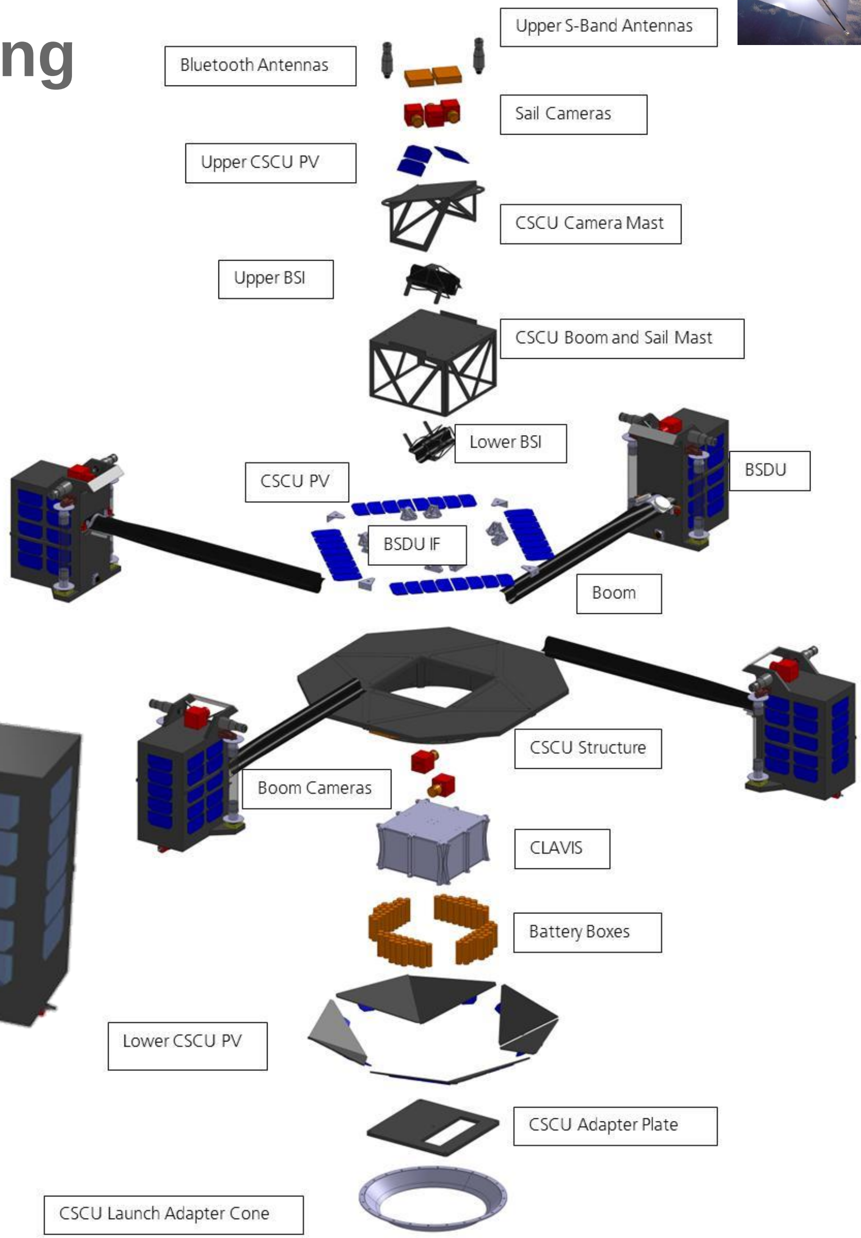
near-term technology: Solar sail with carefree handling – GOSSAMER-1 EQM

- the 3-step DLR-ESTEC GOSSAMER Roadmap to Solar Sailing was set up in 2009 to develop key technolgies for science missions
- 1st step: GOSSAMER-1 EQM was built & qualification tested
- development was stopped after reaching TRL 5
- a PFM design was ready to proceed
- a launch opportunity was available
- all-launchers load envelope



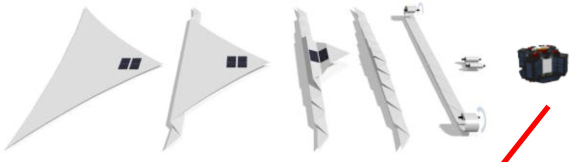


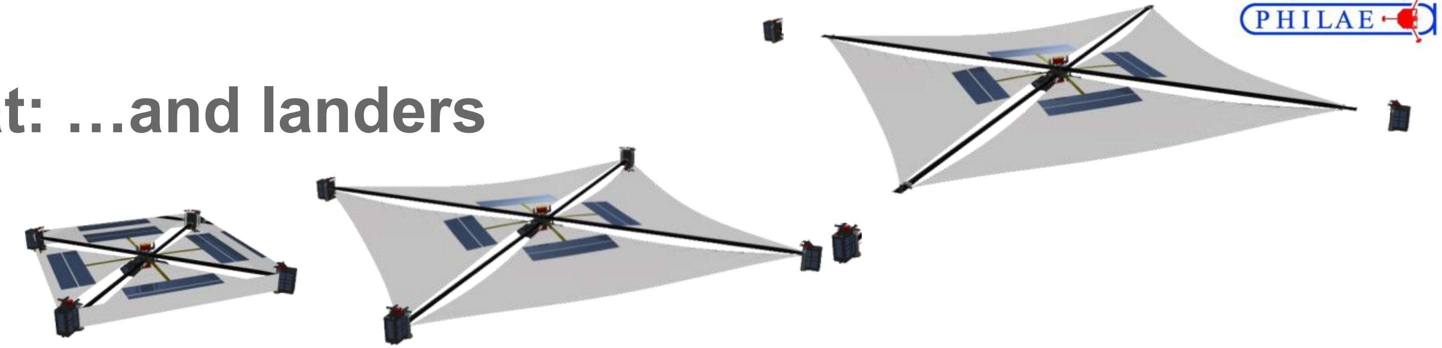
≈30…≤37.6kg, 79·79·50 cm³

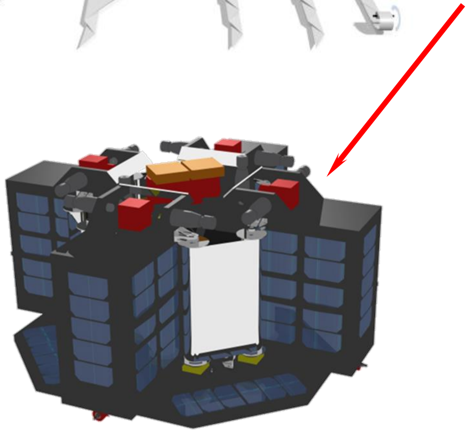


figures: Seefeldt et al., 2016/2017

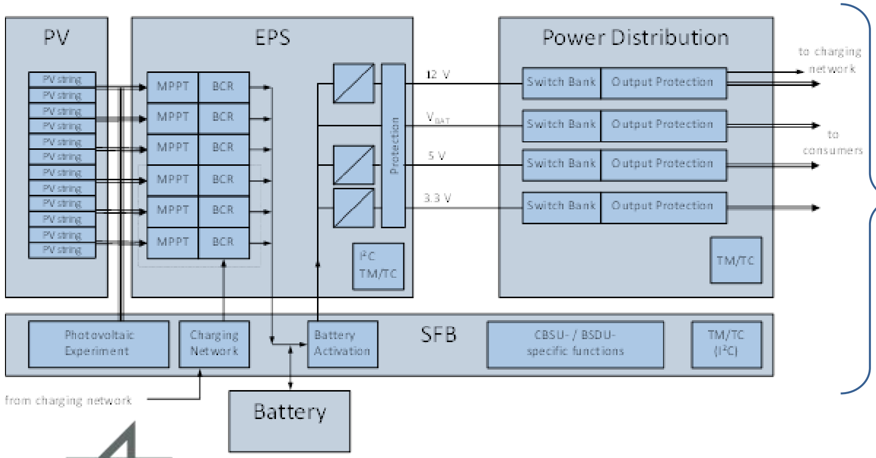
integrating all that: …and landers

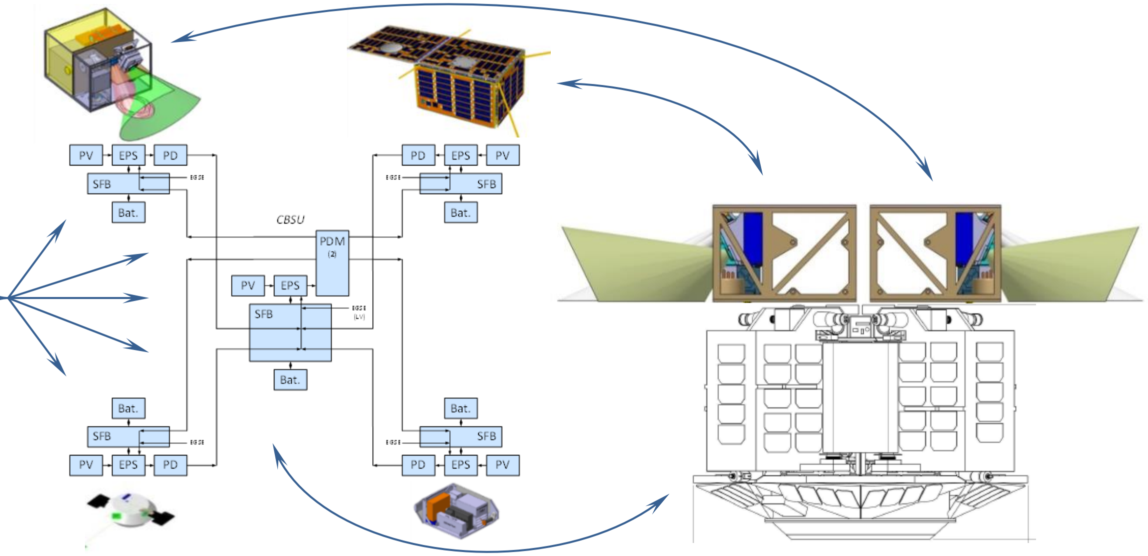


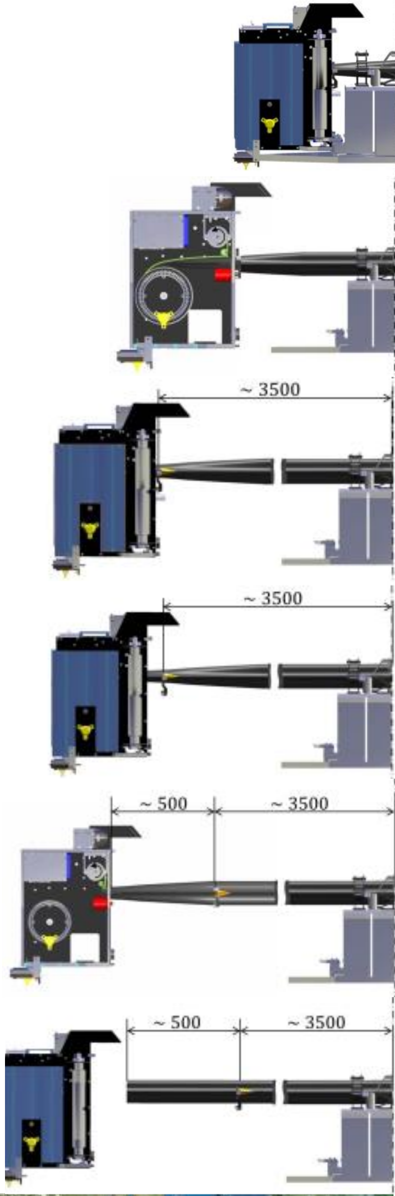




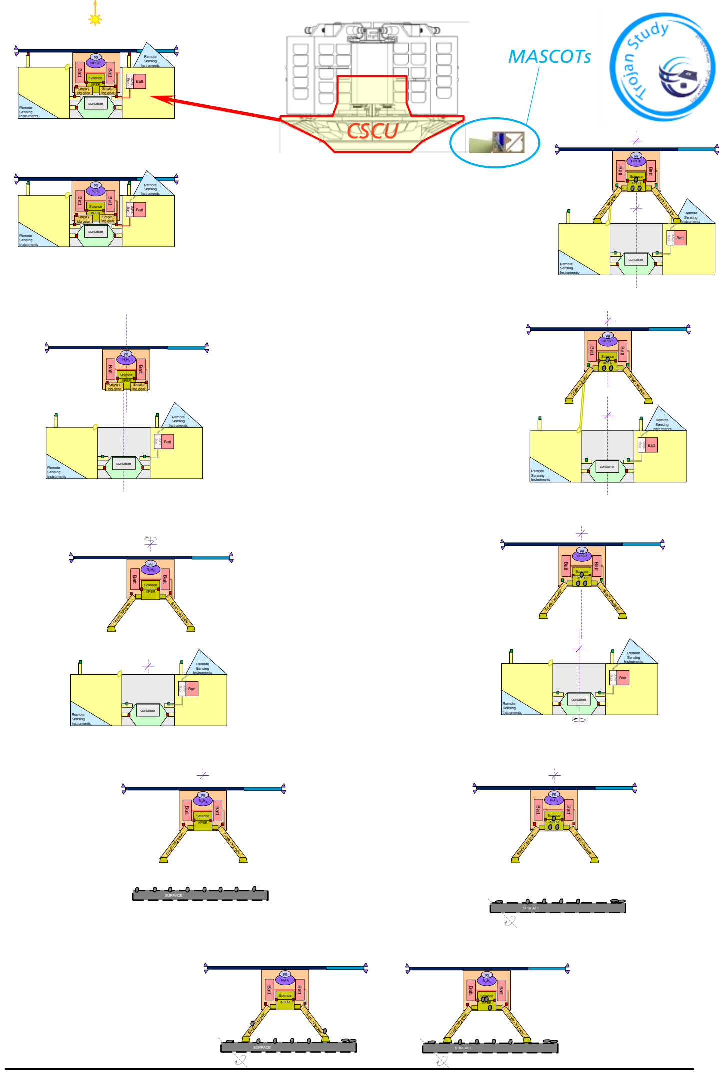
- 1 GOSSAMER sail at launch = 5 independent spacecraft connected to act as one
- electrical – thermal – mechanical face-to-face interfaces enable energy transfer
- additional plane of interfaces for 'payload' side on Central Sailcraft Unit (CSCU)
- interfaces between the CSCU and the 4 Boom Sail Deployment Units (BSDU) already use elements also present in MASCOT, e.g. Umbilical Connectors
- MASCOT already has suitable interfaces to its carrying structure (MESS)
- mutual support of landers and sailcraft extends concept into cruise

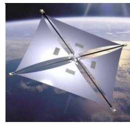






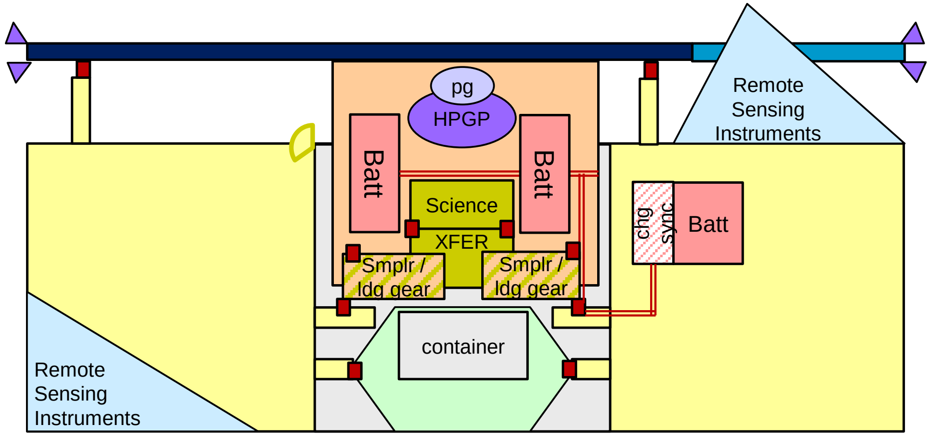
figures : Seefeldt et al., 2016

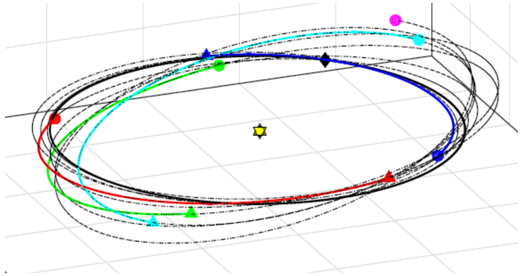




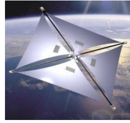
…and returning them to the Earth

- sample return requires propulsion
    - pre-deployment propulsion capability can be useful for large sails
    - propulsion entirely on lander, control divided
- propulsion power drives lander battery & photovoltaics
    - the core sailcraft needs pre-deployment photovoltaics (PV)
- battery shared, mostly on lander
- rigid PV completely on lander
- flexible cruise PV on sail

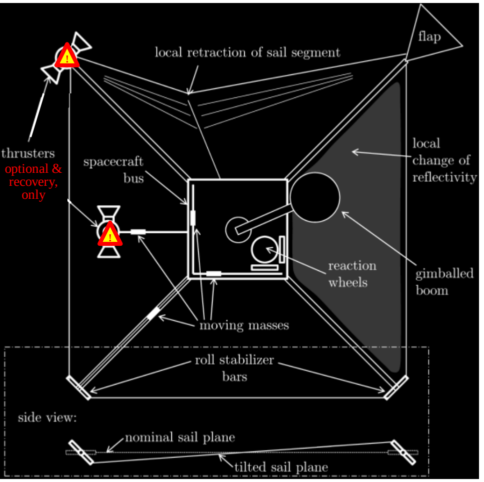




Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//	10 May 2025	26 Feb 2027	657
2000 SG_{344}	123	29 Jun 2027	06 Sep 2028	436
2015 JD_3	164	18 Feb 2029	24 Sep 2030	584
2012 KB_4	160	04 Mar 2031	29 Sep 2032	576
2008 EV_5	*160*	*18 Mar 2033*	*22 May 2036*	*1161*
Earth	∞			

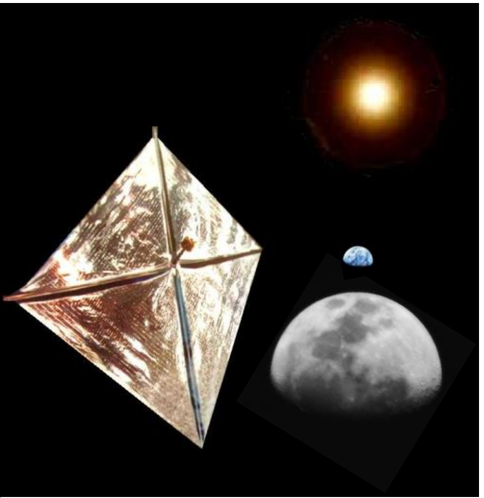


Performance of GOSSAMER technology
benchmark: Multiple NEA Rendezvous trajectories @ $a_c = 0.2\ mm/s^2$



GOSSAMER-2 – high-orbit attitude & thrust vector control

- (20…25 m)² sail area
- orbit where solar radiation pressure is dominant
- implementation of several to "all" control methods
- *thrusters only for recovery*

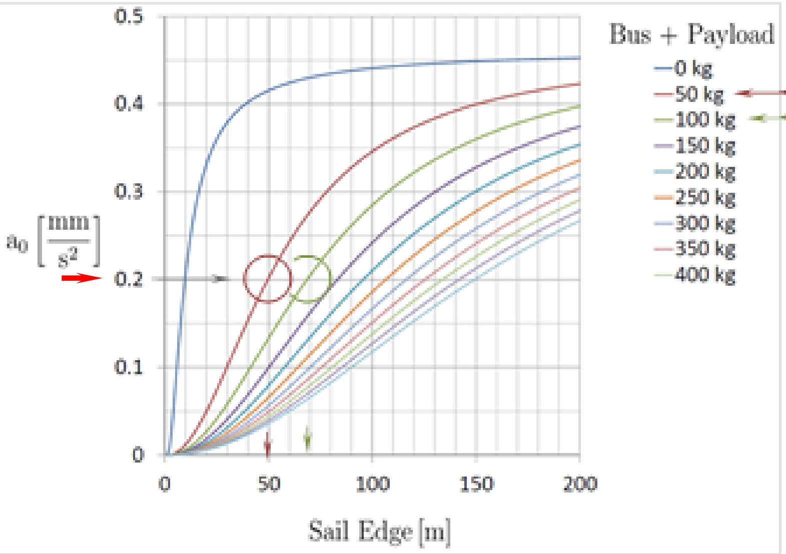


GOSSAMER-3 – all-up proof test

- (50 m)² sail area
- initial orbit high enough to spiral out (sail up)
- **prove that sails can operate science missions**

- GOSSAMER-1 technology:
  - 0.2 mm/s² & 50 kg bus & payload → (50 m)² membrane
  - 0.2 mm/s² & 100 kg bus & payload → (70 m)² membrane
  - 0.2 mm/s² & 150 kg bus & payload → (85 m)² membrane

➔ ESPA / ASAP compatible micro-spacecraft

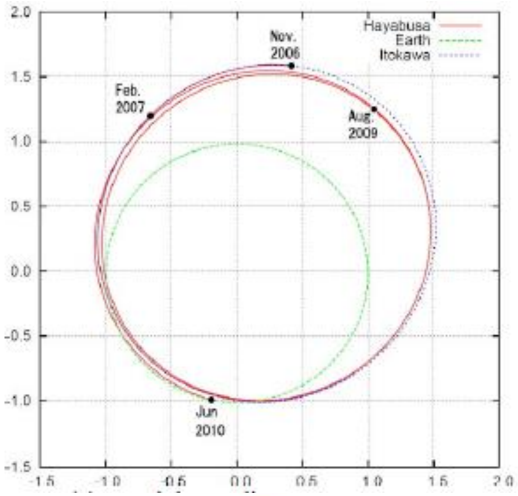


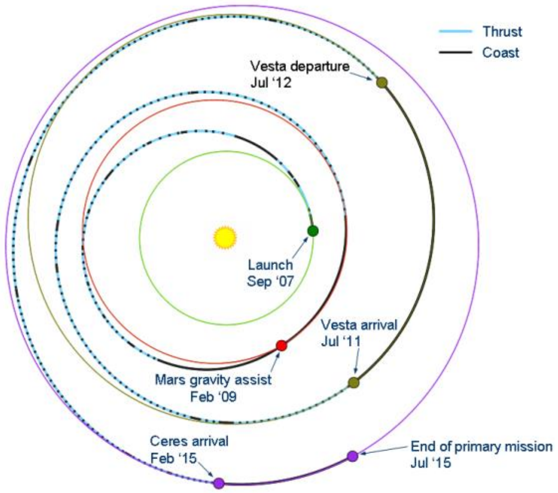
Bus (Gos-1 + X-Band)	≈30 kg
Mother Spacecraft Science Instruments	≈10 kg

Lander	
PHILAE	98 kg
SPS Lander	100kg
1 MASCOT	10 kg
5 MASCOTs	50 kg +10 kg support struc.ture

images adapted from Dachwald et al. & ENEAS study additional images: Moon: Jérôme Salez (wiki), Earth: Bill Anders, Apollo 8, NASA

state of the art: DAWN – 2-asteroid rendezvous
HAYABUSA & HAYABUSA2 – 1-asteroid sample-return





- HAYABUSA2 is currently at (162173) Ryugu
  - **Δv capability ≈ 3.2 km/s** from 66 kg Xe propellant
  - **up to ≈ 3.5 km/s** if filled up to 73 kg Xe capacity
- HAYABUSA returned samples from (25143) Itokawa
  - **Δv capability ≈ 4.0 km/s** from 66 kg Xe propellant
- DAWN orbited (4) Vesta & orbits (1) Ceres
  - **Δv capability ≈ 13 km/s** from 275 kg Xe propellant

common feature:
high-performance electric propulsion

…and the limit?

- SESAME (Maiwald & Marchand, 2016)
  - science payload 33 kg (orbiter) + 5* 4.3 kg (landers)
  - trajectory to **5 NEAs** of ≈200 candidates
  - ***primarily* astrodynamic target selection**
  - targets tied to launch date

Property	Value
Departure Date from Earth	21 March 2023
Arrival @ 5th target	26 February 2030
Total Δv	16.6 km/s
Wet mass	1,571 kg
Xenon fuel mass	451 kg
Bi-propellant mass	125 kg

Table 7: Mission parameters of SESAME

Target Body Data	Absolute Magnitude (H)	Orbit Condition Code (OCC)	Observation opportunities prior launch
$2001QJ_{142}$	23.4	6	2012
$2000SG_{344}$	24.8	2	none
$2009OS_5$	23.6	5	2014-2020
2007YF	24.8	5	2021
$1999AO_{10}$	23.9	6	2018, 2026

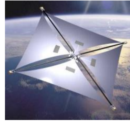
Table 8: Mission target data

Body	Arrival Date	Departure Date
Earth	-	21 Mar 2023
$2001QJ_{142}$	31 Jan 2024	22 Jul 2024
$2000SG_{344}$	9 Oct 2025	8 Mar 2026
$2009OS_5$	27 Mar 2027	28 Sep 2027
2007YF	16 Dec 2028	19 May 2029
$1999AO_{10}$	26 Feb 2030	4 Sep 2030

Table 9: Trajectory data.

figures: Kuninaka et al., 2009; Nishiyama et al., 2015 , NASA/DLR, JAXA Maiwald & Marchand, 2016

DLR



…and now without fuel tank:
Multiple NEA Rendezvous by Solar Sail

- solar sailing provides propulsion *__not__* limited by an amount of fuel

– then what's the next limit? –

how well it is designed, built, tested, flown & fixed

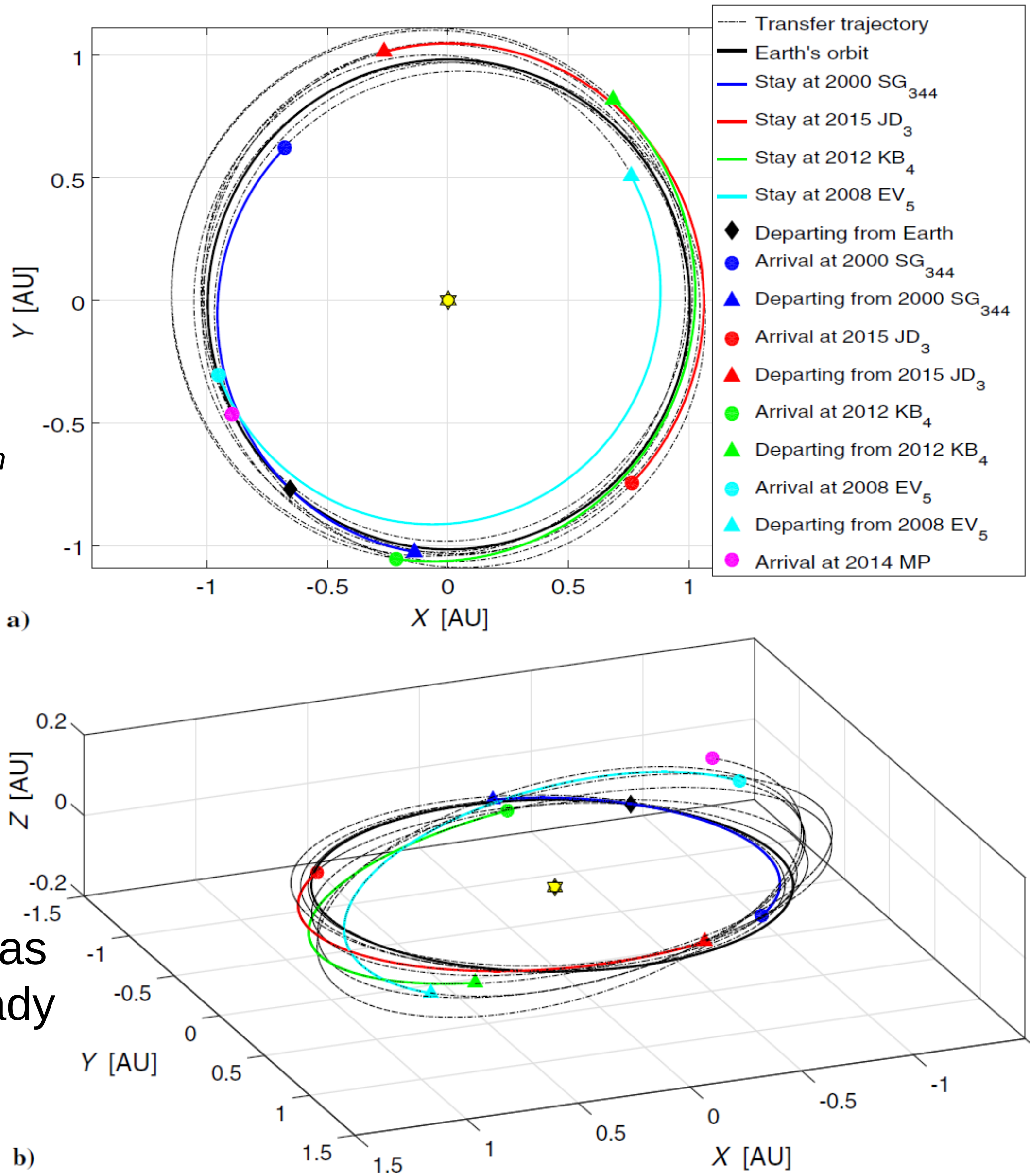
mechanisms have been fixed in space without astronauts around: e.g. Voyager 1 scan platform

- recent studies (Peloni et al., 2016-2018) demonstrate
  - 5 NEA stays for ≥100 days, each, in 10 years
  - accumulated **Δv >50 km/s** @ a_c = 0.2 mm/s²

  ➔ asteroid-oriented target selection is feasible

  ➔ at-launch & ***__in-flight target change capability__***

- target-flexible Multiple NEA Rendezvous for planetary science was identified as a mission type uniquely feasible with solar sail already by the GOSSAMER Roadmap Science Working Groups



figures: Peloni, Ceriotti, Dachwald, 2016

5 NEAs in 10 years
– many times a day

even restricted to PHA & NHATS targets, only,…

- there are 100’s of possible NEA sequences for each launch date
- targets can be changed *any* time while in cruise or rendezvous
- *now* available sail technology is sufficient

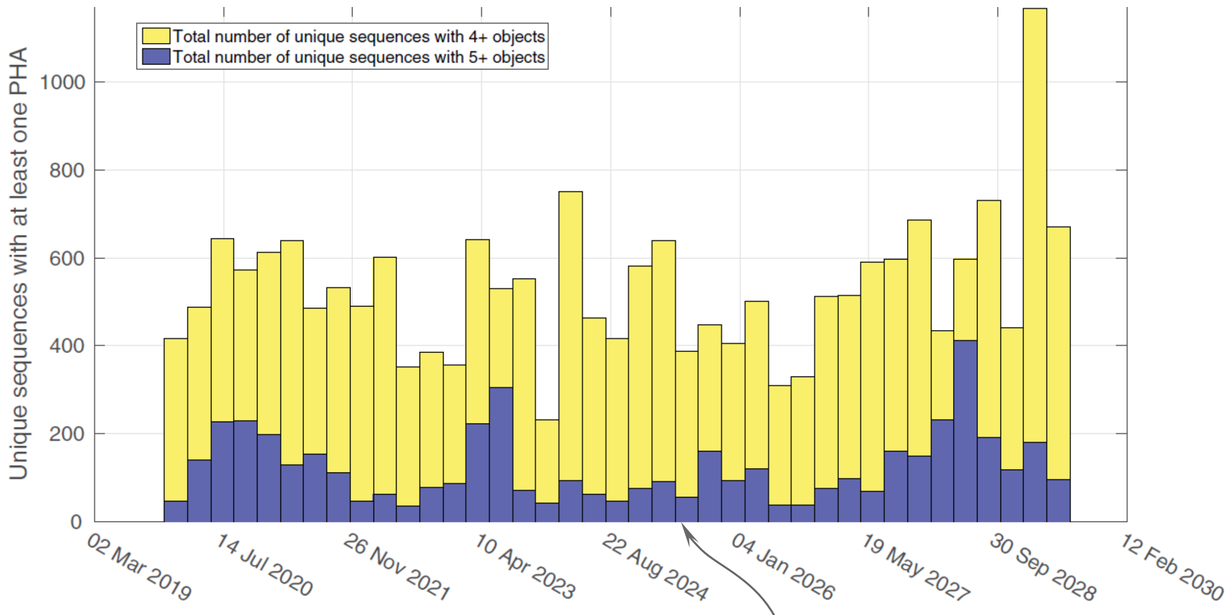


Fig. 7 Number of unique sequences with at least one PHA and four encounters as a function of the launch date.

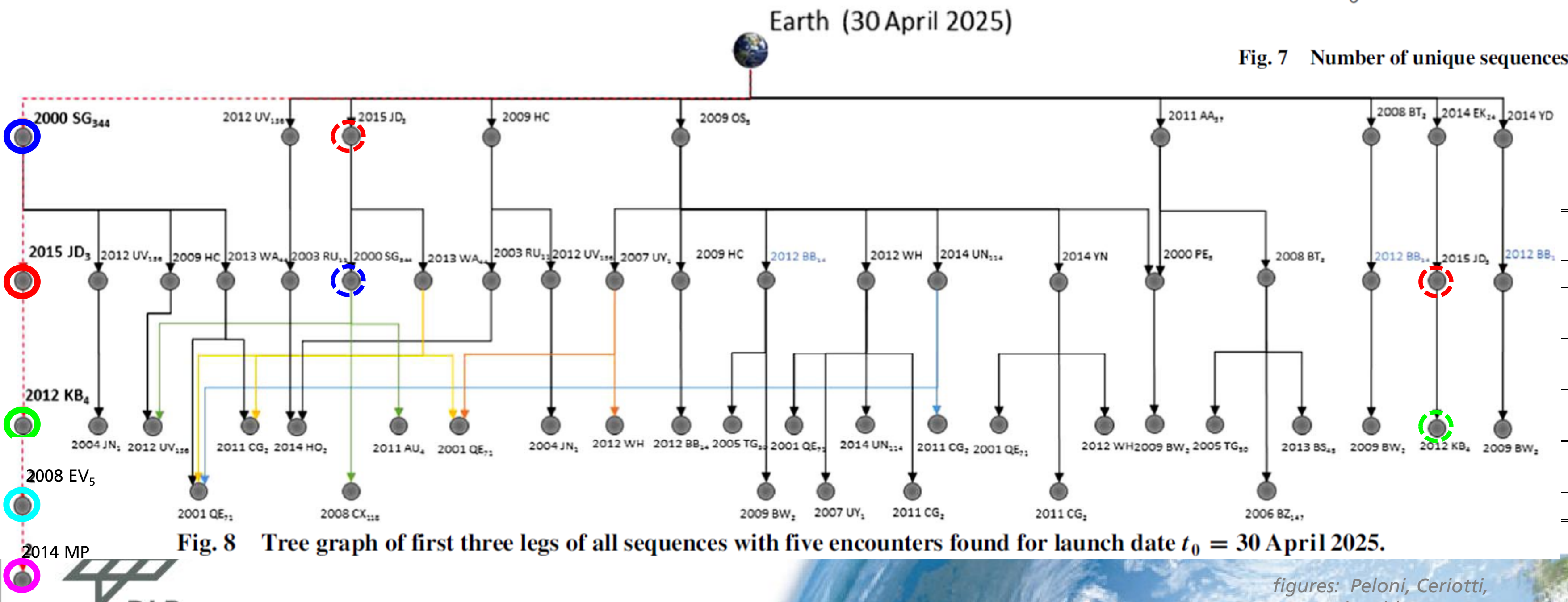


Fig. 8 Tree graph of first three legs of all sequences with five encounters found for launch date t_0 = 30 April 2025.

Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//			
		10 May 2025	26 Feb 2027	657
2000 SG_{344}	123			
		29 Jun 2027	06 Sep 2028	436
2015 JD_3	164			
		18 Feb 2029	24 Sep 2030	584
2012 KB_4	160			
		04 Mar 2031	29 Sep 2032	576
2008 EV_5	171			
		20 Mar 2033	30 Sep 2034	560
2014 MP	//			

figures: Peloni, Ceriotti, Dachwald, 2016

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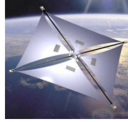
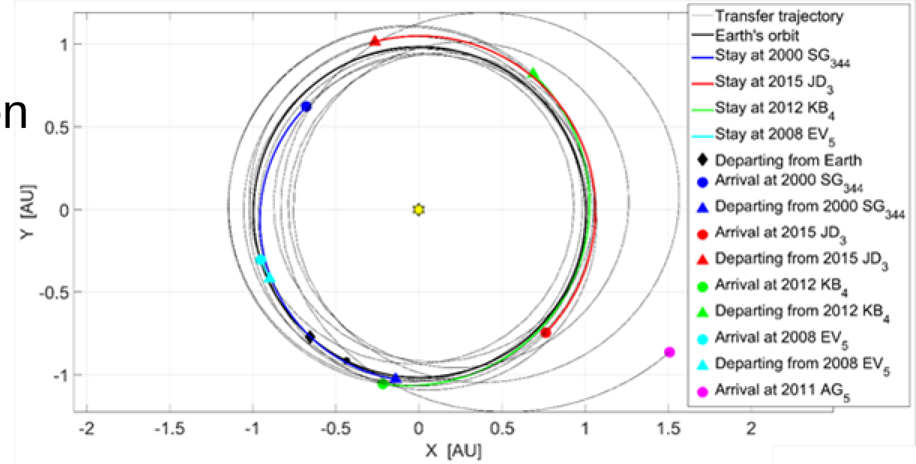


…and then still (have to) change your mind,…
– going after (fictitious) impactors by sail

- 2011 AG_5 – the PDC 2013 Exercise impactor, hits February 3rd, 2040
- fully optimized MNR mission launched in 2025 *can* be diverted to *rendezvous* 2011 AG_5 *in time*

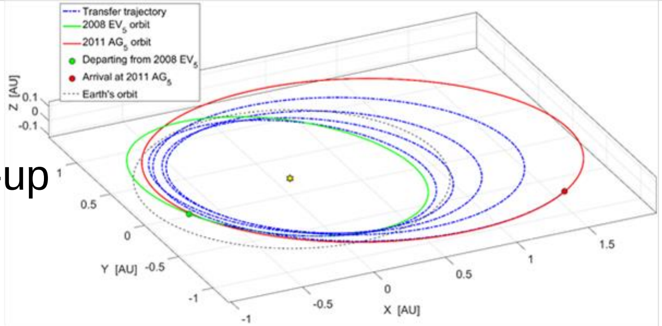
- optimized trajectory change:
- diverting from an *ongoing* MNR mission
- *rendezvous* feasible at a_c = 0.2 mm/s²

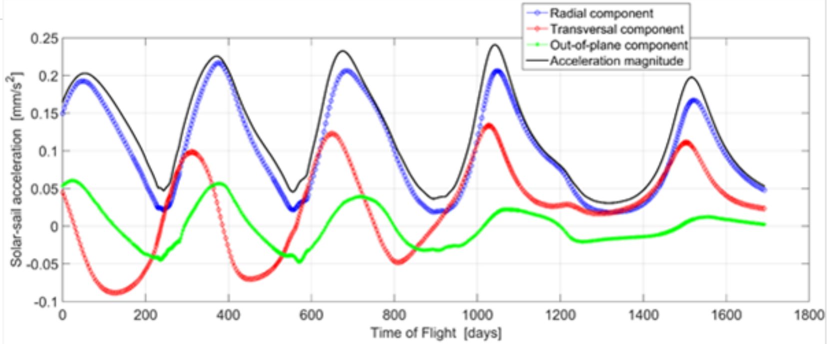


Object	Stay time [days]	Start	End	Time of flight [days]
Earth	//	10 May 2025	26 Feb 2027	657
2000 SG_{344}	123	29 Jun 2027	06 Sep 2028	436
2015 JD_3	164	18 Feb 2029	24 Sep 2030	584
2012 KB_4	160	04 Mar 2031	29 Sep 2032	576
2008 EV_5	*7.5*	*07 Oct 2032*	*25 May 2037*	*1691*
2011 AG_5	*987 to ⊕*			

Object	2000 SG_{344}	2015 JD_3	2012 KB_4	2008 EV_5	2011 AG_5
Orbital type	Aten	Amor	Amor	Aten	Apollo
Semi-major axis [AU]	0.977	1.058	1.093	0.958	1.431
Eccentricity	0.067	0.009	0.061	0.083	0.390
Inclination [deg]	0.111	2.730	6.328	7.437	3.681
Absolute magnitude [mag]	24.7	25.6	25.3	20	21.8
Estimated size [m]	35 – 75	20 – 50	20 – 50	260 – 590	110– 240
EMOID [AU]	0.0008	0.054	0.073	0.014	0.0002
PHA	no	no	no	yes	yes
NHATS	yes	yes	yes	yes	no

- PDC 2017 target:
  - hits in 2027
  - too soon for this 2025 launch study
  - 2020 launch can reach it only in 2030
  - useful mission: tracking, keyhole clean-up

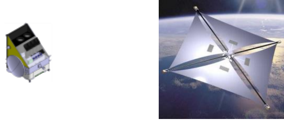




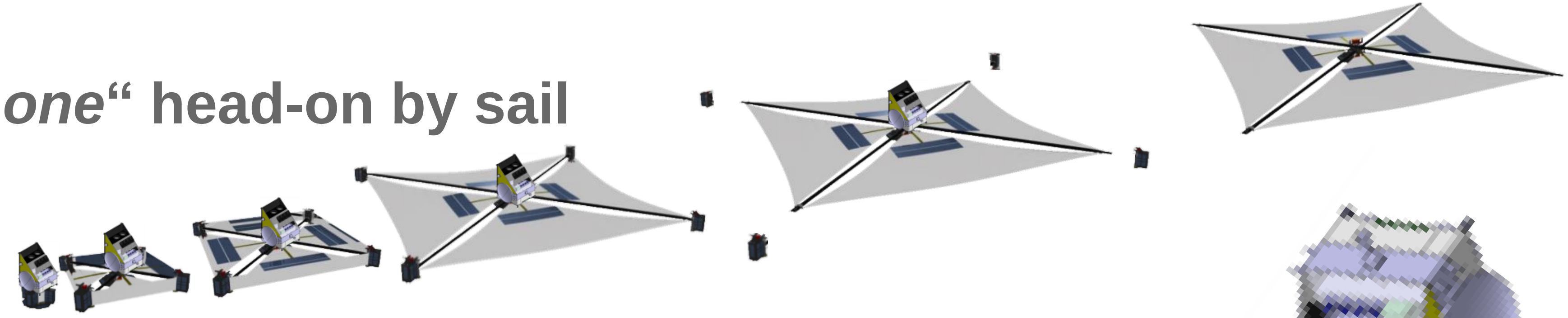
EXERCISE

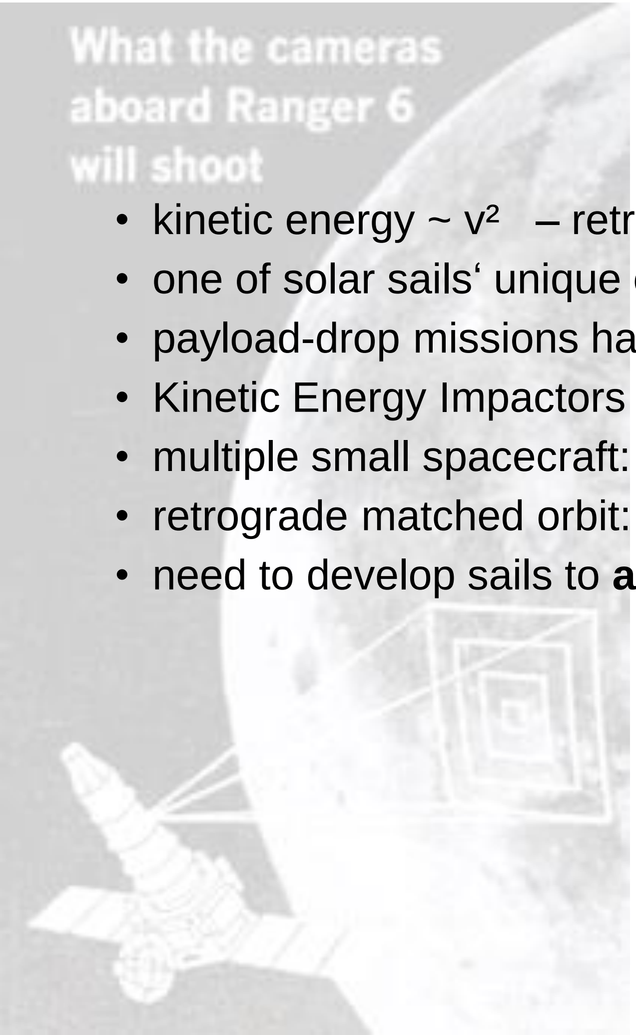
NOT A REAL WORLD EVENT

figures & tables extended from: Peloni, Ceriotti, Dachwald, 2016

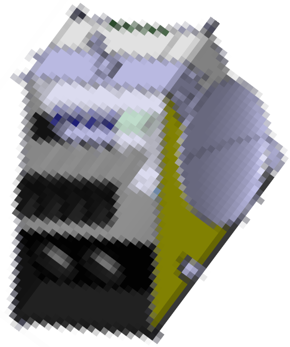


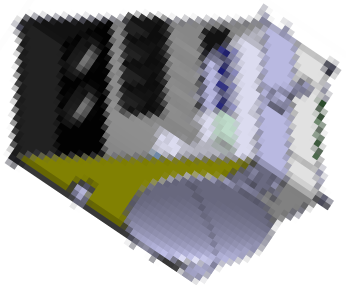
…and finally, fix it.
going for "*the one*" head-on by sail

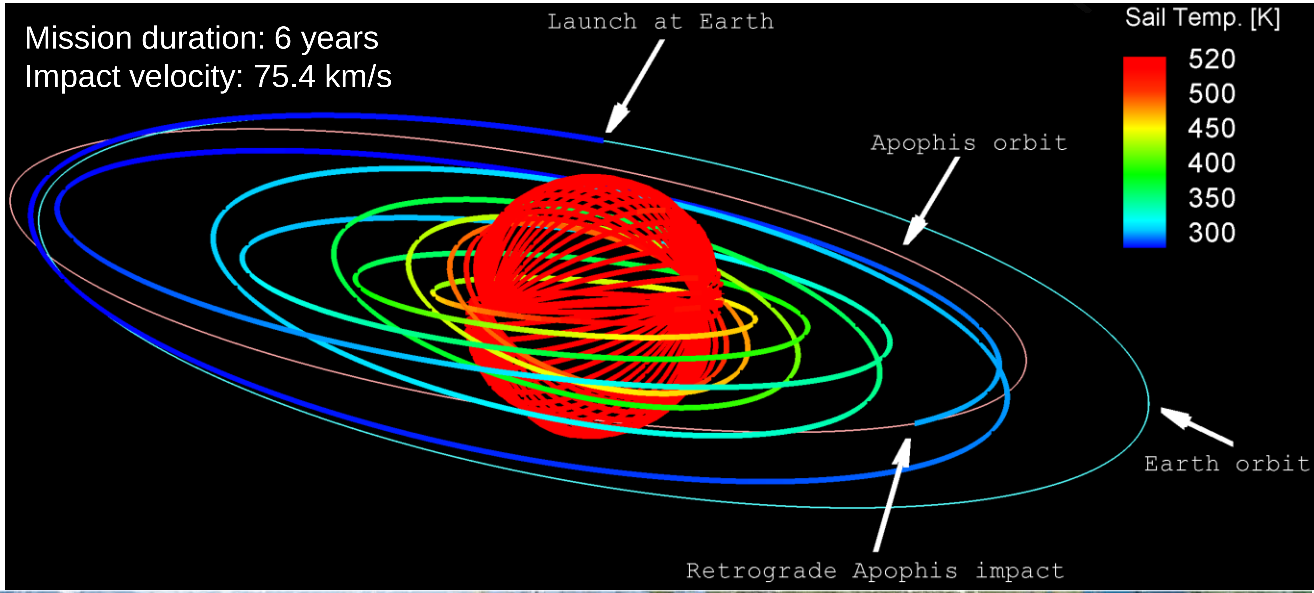




- kinetic energy ~ v^2 – retrograde orbit maximizes energy
- one of solar sails' unique capabilities: orbit cranking to *i* >>60°
- payload-drop missions have been studied, e.g. Solar Polar Orbiter / Imager
- Kinetic Energy Impactors don't care what they are made of – and in how many pieces they come
- multiple small spacecraft: add robustness
- retrograde matched orbit: re-try capability
- need to develop sails to $\mathbf{a_c \approx 0.5\ mm/s^2}$







figures NASA; Dachwald, Kahle, Wie, 2006/2007

Conclusions

- currently available qualified solar sail and recently flown lander technology enables
  - small spacecraft approach to asteroid related science and applications missions
  - large-scale exploration of the entire Near Earth Asteroid population
  - mass-to-orbit efficient mitigation
- complete solar sail technology development is required to realize these missions
- the experience of MASCOT refreshes the original responsive approach to space
- small-spacecraft technology leads towards an affordable development through re-use

thank you for your attention! – don’t hestitate to send in questions ☺